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IGNITION ENERGIES OF SOLID PROPELLANTS

29 APRIL 1954



U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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IGNITION ENERGIES OF SOLID PROPELLANTS

Prepared by:

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ABSTRACT: This is a progress report on an investigation to test the theory of Lewis and von Elbe (1) for the ignition of propellants.

Information from two types of experiments was utilized to calculate ignition energies per unit area and "linear" surface temperatures. At the University of Michigan (2,3) M2 propellant was ignited by hot gas under forced convection, while at the Franklin Institute (4,5) ignition occurred by free convection (including radiative) heat transfer. From these experiments it is shown that, for constant gas flow rate (forced convection) and constant gas pressure (free and radiative convection), the ignition energy per unit area decreases with increasing gas temperature, which is in accordance with the theory. The ignition times are too long to allow determination of whether a minimum ignition energy per unit area exists. It is proposed to extend the investigation to the short ignition times provided by the adiabatic compression technique developed at NOL.

Explosives Research Department
U.S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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Under Task NOL B2d-2-1-54 the Naval Ordnance Laboratory is charged with conducting research on the fundamentals of ignition and combustion. This report is concerned with the amount of energy per unit area necessary to ignite a propellant under given conditions.

JOHN T. HAYWARD
Captain, USN
Commander

PAUL M. FYE
By direction

[illegible]

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IGNITION ENERGIES OF SOLID PROPELLANTS

I. TABLE OF SYMBOLS

| | | |
|-----------------|--|------------------------|
| A | arbitrary constant | dimensionless |
| c | constant pressure heat capacity | any units |
| D | diameter of propellant grain | any units |
| f | energy flux | any units |
| G | gas mass flow rate | lbs/hr ft ² |
| h | reduced heat transfer coefficient | 1/cm |
| H | heat transfer coefficient | any units |
| k | thermal conductivity of gas | any units |
| K | thermal conductivity of propellant | any units |
| n | arbitrary exponent | dimensionless |
| q | ignition energy per unit area | cal/cm ² |
| t | time | any units |
| T _g | gas temperature | °K |
| T _o | ambient temperature | °K |
| T _s | surface temperature | °K |
| T' _s | assumed surface temperature | °K |
| v | temperature above ambient at x and t | °K |
| v _s | surface temperature above ambient at t | °K |
| V | gas temperature above ambient | °K |
| V | fictitious gas "temperature" | °K |
| x | distance from surface into propellant | any units |
| | diffusivity of propellant | any units |

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I. TABLE OF SYMBOLS (contd.)

| | | |
|--------|---------------|-----------|
| τ | ignition time | any units |
| μ | gas viscosity | any units |

Subscripts:

| | |
|---|------------|
| G | "greatest" |
| L | "least" |

II. INTRODUCTION

The ignition theory advanced by Lewis and von Elbe states that the amount of energy per unit area, q , necessary to ignite a propellant surface depends upon the energy source temperature. The lower that temperature, the greater must q be. Also as the temperature increases, q approaches a minimum value. This minimum q is thought to be approximately equal to the excess enthalpy associated with the combustion wave.

The purpose of this investigation has been to test the theory and to demonstrate the conditions under which it is valid.

The equations for the local heat transfer coefficients for forced convection, derived by the University of Michigan (6), enabled us to test this theory under conditions which are similar to those found in practical ignition systems. Because of the type of dependence of these coefficients upon the assumed surface temperature of the grain, it is possible to calculate "greatest" and "least" coefficients for every experimental run. Hence, for every run, this permits the calculations of "greatest" and "least" value of q and surface temperature, T_s .

III. MATHEMATICAL MODEL

To calculate T_s and q at the time of ignition, τ , it is necessary to solve the classical heat conduction equation for a cylinder being heated by convection. To simplify the problem a little, one can substitute a semi-infinite solid for a semi-infinite cylinder. This is possible because the diffusivity of the class of solid propellants is extremely small and the order of ignition times involved does not allow for any appreciable temperature rise much below the surface. Hence, to a temperature wave propagating into the solid from the surface, the solid appears to be of infinite depth i.e. a semi-infinite solid. The problem is reduced to that of finding v_s , the surface temperature above ambient, and q as functions of t for a semi-infinite solid being heated by convection and/or radiation from a medium at temp V above ambient; the initial temperature of the solid is zero.

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The equation to be solved is

$$(1) \quad \frac{\partial v}{\partial t} = \kappa \frac{\partial^2 v}{\partial x^2}$$

for the boundary conditions

$$(2) \quad \begin{aligned} -\frac{\partial v}{\partial x} + h v &= V \quad \text{at } x=0 \\ v(x,0) &= 0 \end{aligned}$$

The solution (8) is

$$(3) \quad \frac{v(x,t)}{V} = \operatorname{erfc} \frac{x}{2\sqrt{\kappa t}} - e^{hx + \frac{h^2}{\kappa} t} \operatorname{erfc} \left(\frac{x}{2\sqrt{\kappa t}} + h\sqrt{\kappa t} \right)$$

where $\operatorname{erfc} \xi = \frac{2}{\sqrt{\pi}} \int_{\xi}^{\infty} e^{-u^2} du$

Putting $x = 0$ and $t = \tau$, one gets for the surface temperature rise at the ignition time,

$$(4) \quad v_s(\tau) = V \left\{ 1 - e^{\frac{h^2}{\kappa} \tau} \operatorname{erfc} h\sqrt{\kappa \tau} \right\}$$

To calculate q we integrate the flux over the ignition interval, and this is

$$(5) \quad q(0,\tau) = \int_0^{\tau} f(0,t) dt$$

where $f(x,t) = -\kappa \frac{\partial v(x,t)}{\partial x}$

We have

$$(6) \quad \frac{\partial v(x,t)}{\partial x} = -hV e^{hx + \frac{h^2}{\kappa} t} \operatorname{erfc} \left(\frac{x}{2\sqrt{\kappa t}} + h\sqrt{\kappa t} \right)$$

The surface flux is

$$(7) \quad f(0,t) = \kappa hV e^{\frac{h^2}{\kappa} t} \operatorname{erfc} h\sqrt{\kappa t}$$

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Substituting (7) into (5) yields

$$(8) \quad \frac{q(0, \tau)}{K h V} = \int_0^{\tau} e^{-h^2 k t} dt - \frac{2}{\sqrt{\pi}} \int_0^{\tau} e^{-h^2 k t} dt \int_0^{h\sqrt{k t}} e^{-u^2} du$$

After evaluating the second integral by parts we finally get

$$(9) \quad q = \frac{KV}{hk} \left\{ e^{-h^2 k \tau} \operatorname{erfc} h\sqrt{k\tau} - 1 + \frac{2}{\sqrt{\pi}} h\sqrt{k\tau} \right\}$$

where q will replace $q(0, \tau)$ and v_s will replace $v_s(\tau)$ from now on.

(9) can be rewritten, by substituting (4) into it, giving (9')

$$q = \frac{KV}{hk} \left\{ \frac{2}{\sqrt{\pi}} h\sqrt{k\tau} - \frac{\sqrt{2}}{V} \right\}$$

IV. EXPERIMENTAL AND CALCULATED RESULTS

It is desired to evaluate v_s and q for the Michigan and the Franklin Institute data.

The Michigan equation for the heat transfer coefficient, H , between a moving gas stream and a right circular cylinder where axis is normal to the gas flow is

$$(10) \quad H = A \frac{h}{D} \left(\frac{c\mu}{k} \right)^{\frac{1}{3}} \left(\frac{GD}{\mu} \right)^n \left(\frac{T_g}{T_f} \right)^{0.12}$$

The h used in eq(2) is defined by

$$(11) \quad h = \frac{H}{K}$$

Hence

$$(12) \quad h = \frac{A}{K} \frac{h}{D} \left(\frac{c\mu}{k} \right)^{\frac{1}{3}} \left(\frac{GD}{\mu} \right)^n \left(\frac{T_g}{T_f} \right)^{0.12}$$

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For any one experimental run all the constants of (12) are known except T'_s which increases from ambient temperature, T_0 . Therefore h depends upon our knowledge of T'_s . But by eq(4), we must know h in order to calculate $T_s = T_0 + v_s$. This does not make the situation hopeless, for by the following method we can demonstrate that the indeterminancy in v_s is very small compared to the actual v_s .

For a given r during any one experiment, the values of v_s and q will be greatest when h is greatest. Similarly, the values of v_s and q will be smallest when h is least. From (12) it is easily seen that

$$(13) \quad h_g \sim \left(\frac{1}{T'_{s,g}} \right)^{0.12}$$

and

$$(14) \quad h_L \sim \left(\frac{1}{T'_{s,L}} \right)^{0.12}$$

By replacing $T'_{s,L}$ by T_0 in (13) we get h_0 and hence v_{s_0} and q_0 by (4) and (9). Then replacing T'_{s_0} by $T_0 + v_{s_0}$ in (14) we obtain h_L and hence v_{s_L} and q_L . We now have

$$(15) \quad v_{s_L} < v_s < v_{s_0} \\ q_L < q < q_0$$

Analysis of the data shows that

$$(16) \quad v_{s_0} - v_{s_L} \ll v_s \\ q_0 - q_L \ll q$$

In their report, the Franklin Institute had calculated the surface temperatures for the Michigan work using the latter's equation for the local heat transfer coefficient. Since their values of v_s must obey (15) and (16), we have used these values in (9') to calculate the q 's which also obey (15) and (16). For the range investigated q_0 and q_L differ by 0.1 - 0.2 cal/cm². The lower limit is for shorter ignition times.

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At this point it must be pointed out that the ignition time, in all cases, was determined by actuation of a photocell by the propellant flame.

In Table 1 are given the calculated q 's for forced convection using an 80% N_2 - 20% O_2 gas.

In Tables 2, 3, and 4 are given the calculated q 's for free convection for H_2 , N_2 , and air, respectively. The v_g 's shown are those previously calculated (5).

In Table 5 are given q_G , q_L , v_{sG} , v_{sL} and the experimental conditions for a different set of forced convection experiments (3). These are characterized by much shorter ignition times. The values of $A = 0.81$ and $n = 0.54$ were used in (10).

Figures 1, 2, 3, and 4 are the plots of data in Tables 1, 2, 3, and 4, respectively.

Tables 2, 3, and 4 are plotted in such a manner in Figures 5, 6, and 7 that each Figure represents a constant pressure level.

The physical constants used are reported in the Michigan and Franklin Institute reports.

V. INTERPRETATION AND CONCLUSIONS

Since the model used allowed for energy transfer only from a hot gas to a propellant, the values of v_g and q represent those quantities at the end of the ignition interval, τ , if no chemical reaction had taken place in the propellant.

From Figures 1, 2, 3, and 4 and Table 5, one can see that for all runs at constant flow rate or constant pressure, the values of q decrease with increasing gas temperature. Here we see that the q necessary to ignite the propellant surface must depend not only upon the energy source temperature, as stated in Reference 1, but also upon the flow rate or pressure level for convective processes.

The effect of pressure upon q varies markedly between the three gases for natural convection. In Figures 2, 3, and 4 it is seen that if we consider the gas at constant temperature an increase in pressure gives rise to an increase in q for helium but a decrease in q for nitrogen and

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the 80% N_2 - 20% O_2 mixture. This inversion cannot be explained at the present moment. We can, however, speculate as to the cause.

Suppose propellant ignition was determined, in addition to the assumed convective heat transfer, by a gas-solid phase chemical reaction. Since ignition times are determined by photocell activation due to the propellant flame radiation, any phenomenon which would cause the delay of the flame reaction would increase τ and, by (9), q . The degree of diffusion of the inert gases, He and N_2 , into the gas reaction zone next to the propellant surface would vary according to the pressure levels, and the mobility of the inert molecules compared to those of the gas products at any particular level. Thus, one may suppose that the diffusion process could cause the inversion. It must be admitted that this is a very sketchy description of the hypothesis.

On many of the plots in Figures 2, 3, and 4 the 300 psig curves tend to fall out of place when compared with the other pressure levels. The experimenters (5) feel that due to experimental difficulties it is not possible to determine with certainty whether or not any apparent exceptions in their calculations (hence in our's) are significant.

It is important to note that within the range of experimental results used the lowest value of q is 1.7 cal/cm². This value is in agreement with minimum ignition energies obtained from previous (9) steady state burning results. These gave a value of 2.55 cal cm² for the excess enthalpy associated with a combustion wave as measured by integrating under the temperature-distance curve of steady state burning of nitrocellulose strands. The value of 2.0 cal/cm² for the energy associated with the combustion wave was obtained (9) by measuring the heat drain from a burning powder strand to a copper strip cemented to the bottom of the strand. However, there is no evidence to indicate that if the gas temperature is increased, the value of q at ignition could not continue to decrease with shorter ignition times.

VI. FUTURE WORK

At NOL (10) we have been igniting various propellants by adiabatic compression since this method bears close

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resemblance to practical gun and rocket ignition conditions. We can obtain ignition of equivalent semi-infinite propellant cylinders in the order of two or three milliseconds. Attempts are being made to calculate the ignition energies and a "linear" surface temperatures for such very short ignition times under conditions of continuously varying gas temperature and pressure, and mass flow rate. It is hoped that these conditions will allow us to ascertain whether there exists a critical minimum ignition energy per unit area. The computations are necessarily very complex.

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TABLE 1

IGNITION ENERGIES PER UNIT AREA FOR
M2 PROPELLANT USING 80%N₂-20%O₂

OBTAINED FROM UNIVERSITY OF MICHIGAN
DATA FOR FORCED CONVECTION

5.0 SCFM

| <u>V</u> | <u>τ</u> | <u>h*</u> | <u>v_s*</u> | <u>q</u> |
|----------|--------------------------|-----------|-----------------------|----------|
| 290 | 7.65 | 15.36 | 185 | 8.88 |
| 391 | 3.05 | 16.79 | 210 | 6.23 |
| 516 | 1.14 | 18.85 | 224 | 4.01 |
| 540 | 0.768 | 19.04 | 208 | 3.00 |
| 585 | 0.767 | 19.87 | 234 | 3.25 |
| 628 | 0.608 | 20.47 | 234 | 3.02 |
| 646 | 0.535 | 20.68 | 232 | 2.81 |
| 712 | 0.413 | 21.45 | 238 | 2.55 |

3.5 SCFM

| | | | | |
|-----|-------|-------|-----|------|
| 296 | 9.25 | 12.89 | 182 | 9.63 |
| 403 | 3.10 | 14.04 | 197 | 5.85 |
| 529 | 1.26 | 15.75 | 211 | 3.93 |
| 635 | 0.687 | 17.08 | 218 | 2.95 |
| 751 | 0.447 | 18.43 | 233 | 2.56 |
| 764 | 0.456 | 18.42 | 238 | 2.65 |

2.0 SCFM

| | | | | |
|-----|-------|-------|-----|------|
| 322 | 8.82 | 9.66 | 171 | 8.63 |
| 405 | 4.47 | 10.72 | 188 | 6.73 |
| 501 | 2.07 | 11.53 | 191 | 4.59 |
| 632 | 0.873 | 12.70 | 191 | 2.93 |

*Calculated by Franklin Institute (5)

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TABLE 2

IGNITION ENERGIES PER UNIT AREA FOR M2 PROPELLANT USING He
OBTAINED FROM FRANKLIN INSTITUTE DATA FOR FREE CONVECTION AND
RADIATION

| P | V | \bar{V}^{**} | τ | h^* | v_g^* | q |
|-----|-----|----------------|--------|-------|---------|-------|
| 0 | 420 | 599 | 9.12 | 3.57 | 168 | 8.38 |
| | 495 | 767 | 5.82 | 3.61 | 182 | 7.21 |
| | 570 | 957 | 3.52 | 3.69 | 188 | 5.77 |
| | 645 | 1186 | 2.41 | 3.72 | 199 | 5.12 |
| | 795 | 1746 | 1.08 | 3.85 | 213 | 3.55 |
| 50 | 420 | 532 | 8.54 | 5.73 | 205 | 9.88 |
| | 495 | 665 | 4.41 | 5.78 | 204 | 7.04 |
| | 570 | 815 | 3.22 | 5.82 | 223 | 6.52 |
| | 645 | 986 | 2.02 | 5.90 | 227 | 5.28 |
| | 720 | 1178 | 1.28 | 6.00 | 228 | 4.18 |
| | 795 | 1406 | 0.90 | 6.00 | 234 | 3.61 |
| 100 | 395 | 473 | 8.20 | 7.08 | 206 | 9.80 |
| | 495 | 633 | 4.30 | 7.12 | 223 | 7.72 |
| | 570 | 768 | 2.46 | 7.20 | 223 | 5.79 |
| | 645 | 922 | 1.96 | 7.24 | 247 | 5.60 |
| | | | 1.20 | | 203 | 3.62 |
| | 720 | 1095 | 1.23 | 7.32 | 245 | 4.47 |
| | 795 | 1295 | 0.92 | 7.32 | 258 | 3.99 |
| 200 | 420 | 490 | 7.10 | 9.16 | 238 | 10.67 |
| | 495 | 601 | 4.33 | 9.24 | 253 | 8.75 |
| | 570 | 724 | 2.70 | 9.26 | 263 | 6.95 |
| | 645 | 861 | 1.73 | 9.31 | 266 | 5.71 |
| | 720 | 1014 | 1.20 | 9.34 | 273 | 4.87 |
| | 795 | 1183 | 0.86 | 9.42 | 282 | 4.21 |
| 300 | 420 | 479 | 5.32 | 10.83 | 235 | 9.20 |
| | 495 | 585 | 3.50 | 10.90 | 256 | 7.92 |
| | 570 | 700 | 2.06 | 11.00 | 259 | 6.14 |
| | 645 | 828 | 1.38 | 10.96 | 265 | 5.13 |
| | 720 | 969 | 1.00 | 11.02 | 276 | 4.55 |
| | 795 | 1128 | 0.67 | 11.00 | 275 | 3.66 |

*Calculated by Franklin Institute (5)

** \bar{V} is a "temperature" which includes the radiation boundary condition. To calculate v_g and q , \bar{V} is substituted for V in equations 4 and 9. See Reference (4) for details on calculating \bar{V} .

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TABLE 3

IGNITION ENERGIES PER UNIT AREA
FOR M2 PROPELLANT USING N₂

OBTAINED FROM FRANKLIN INSTITUTE
DATA FOR FREE CONVECTION AND RADIATION

| P | V | \bar{V}^{**} | τ | h* | v_B^* | q |
|-----|-----|----------------|--------|------|---------|-------|
| 0 | 420 | 895 | 30.50 | 1.35 | 187 | 16.77 |
| | 495 | 1207 | 15.40 | 1.38 | 192 | 12.44 |
| | 570 | 1588 | 8.90 | 1.40 | 202 | 9.33 |
| | 645 | 2062 | 5.50 | 1.42 | 213 | 7.68 |
| | 720 | 2625 | 3.70 | 1.44 | 228 | 7.40 |
| | 795 | 3306 | 2.60 | 1.46 | 247 | 6.40 |
| 50 | 420 | 722 | 17.50 | 2.53 | 200 | 13.60 |
| | 495 | 941 | 9.30 | 2.56 | 205 | 8.43 |
| | 570 | 1201 | 5.60 | 2.60 | 214 | 8.12 |
| | 645 | 1514 | 3.70 | 2.63 | 227 | 7.17 |
| | 720 | 1886 | 2.45 | 2.65 | 238 | 5.86 |
| | 795 | 2314 | 1.80 | 2.69 | 257 | 5.57 |
| 100 | 420 | 677 | 12.30 | 3.33 | 202 | 11.53 |
| | 495 | 870 | 6.80 | 3.37 | 208 | 8.88 |
| | 570 | 1097 | 4.10 | 3.41 | 215 | 7.17 |
| | 645 | 1369 | 2.70 | 3.42 | 226 | 5.91 |
| | 720 | 1688 | 1.85 | 3.44 | 237 | 5.14 |
| | 795 | 2053 | 1.40 | 3.49 | 257 | 5.05 |
| 200 | 420 | 631 | 8.80 | 4.52 | 208 | 10.17 |
| | 495 | 799 | 5.00 | 4.59 | 216 | 7.89 |
| | 570 | 995 | 3.10 | 4.62 | 224 | 6.36 |
| | 645 | 1223 | 2.10 | 4.66 | 235 | 5.59 |
| | 720 | 1488 | 1.50 | 4.68 | 249 | 4.99 |
| | 795 | 1791 | 1.10 | 4.72 | 264 | 4.53 |
| 300 | 420 | 615 | 5.40 | 5.43 | 194 | 7.44 |
| | 495 | 771 | 3.10 | 5.55 | 200 | 5.81 |
| | 570 | 952 | 2.00 | 5.60 | 210 | 4.74 |
| | 645 | 1162 | 1.35 | 5.64 | 218 | 4.11 |
| | 720 | 1406 | 1.00 | 5.64 | 232 | 3.77 |
| | 795 | 1676 | 0.75 | 5.72 | 247 | 3.46 |

*Calculated by Franklin Institute (5)

**See note in Table 2

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TABLE 4

IGNITION ENERGIES PER UNIT AREA
FOR M2 PROPELLANT USING AIR

OBTAINED FROM FRANKLIN INSTITUTE
DATA FOR FREE CONVECTION AND RADIATION

| <u>P</u> | <u>V</u> | <u>V**</u> | <u>τ</u> | <u>h*</u> | <u>v_s*</u> | <u>q</u> |
|----------|----------|------------|--------------------------|-----------|-----------------------|----------|
| 0 | 420 | 878 | 25.80 | 1.40 | 177 | 14.38 |
| | 495 | 1178 | 11.84 | 1.43 | 173 | 9.54 |
| | 570 | 1547 | 7.69 | 1.46 | 191 | 8.34 |
| | 645 | 2009 | 5.22 | 1.47 | 211 | 6.91 |
| | 720 | 2546 | 3.36 | 1.50 | 223 | 5.39 |
| | 795 | 3187 | 2.17 | 1.53 | 231 | 4.66 |
| 100 | 420 | 664 | 12.02 | 3.50 | 204 | 11.57 |
| | 495 | 851 | 5.84 | 3.56 | 200 | 7.84 |
| | 570 | 1073 | 3.62 | 3.57 | 208 | 6.39 |
| | 645 | 1337 | 2.41 | 3.59 | 219 | 5.47 |
| | 720 | 1646 | 1.57 | 3.60 | 223 | 4.59 |
| | 795 | 2008 | 1.25 | 3.62 | 247 | 4.56 |
| 300 | 420 | 607 | 4.40 | 5.66 | 184 | 6.20 |
| | 495 | 761 | 2.94 | 5.77 | 200 | 5.54 |
| | 570 | 939 | 1.80 | 5.81 | 204 | 4.40 |
| | 645 | 1143 | 1.36 | 5.85 | 223 | 4.07 |
| | 720 | 1377 | 1.00 | 5.89 | 237 | 3.76 |
| | 795 | 1644 | 0.74 | 5.93 | 249 | 3.44 |

*Calculated by Franklin Institute (5)

**See note in Table 2

TABLE 5
"GREATEST" AND "LEAST" SURFACE TEMPERATURE INCREASES AND IGNITION
ENERGIES PER UNIT AREA FOR M2 PROPELLANT USING 80% N2-20% O2
OBTAINED FROM UNIVERSITY OF MICHIGAN
DATA FOR FORCED CONVECTION

| G | V | τ | h_G | h_L | v_{SG} | v_{SL} | q_G | q_L |
|------|------|--------|-------|-------|----------|----------|-------|-------|
| 1220 | 920 | 0.593 | 12.33 | 11.50 | 235 | 222 | 2.90 | 2.78 |
| 3360 | 923 | 0.278 | 21.22 | 19.35 | 267 | 249 | 2.30 | 2.10 |
| 3360 | 1164 | 0.150 | 23.80 | 21.54 | 291 | 263 | 1.78 | 1.65 |

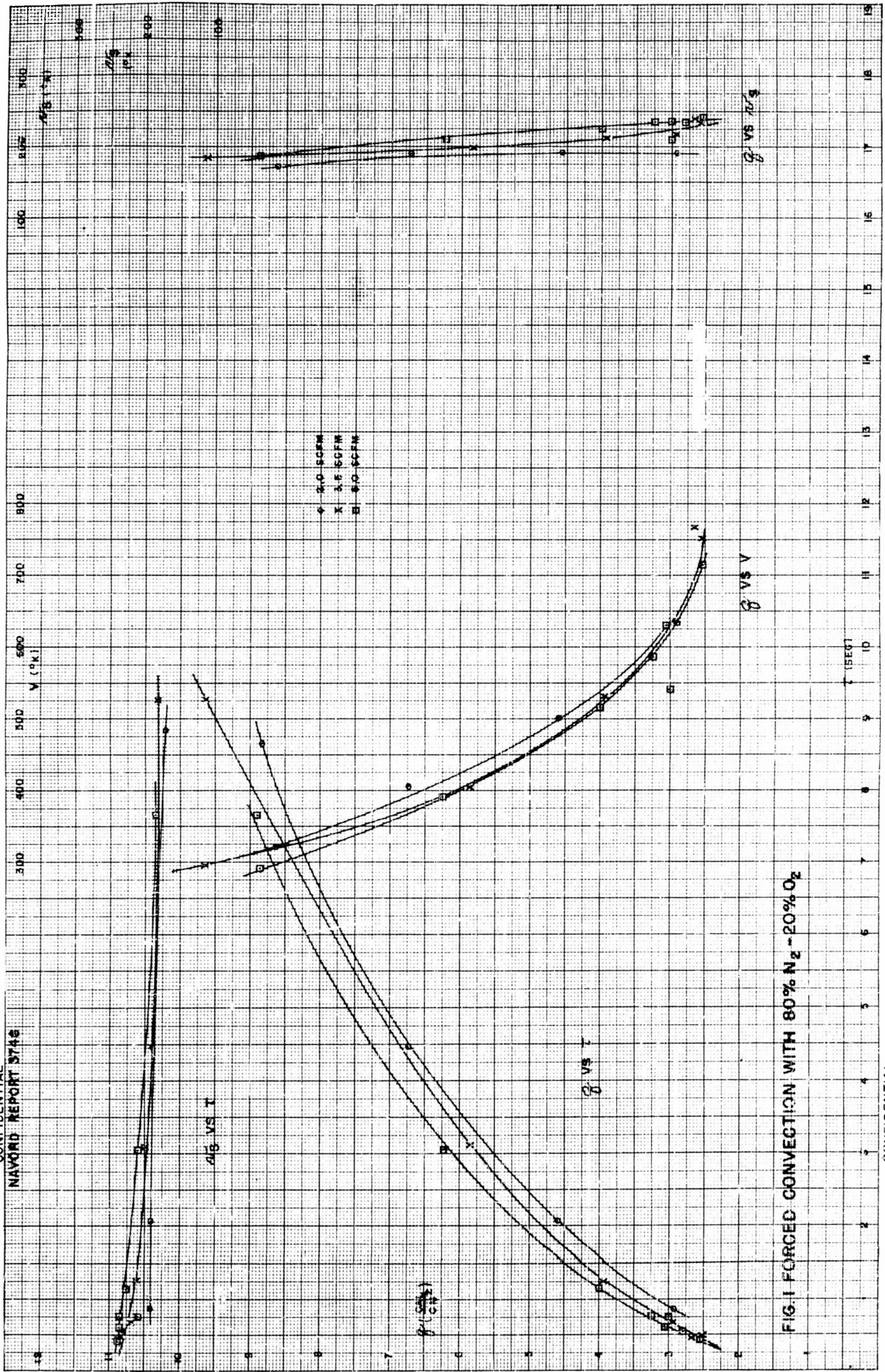


FIG. 1 FORCED CONVECTION WITH 80% N₂ - 20% O₂

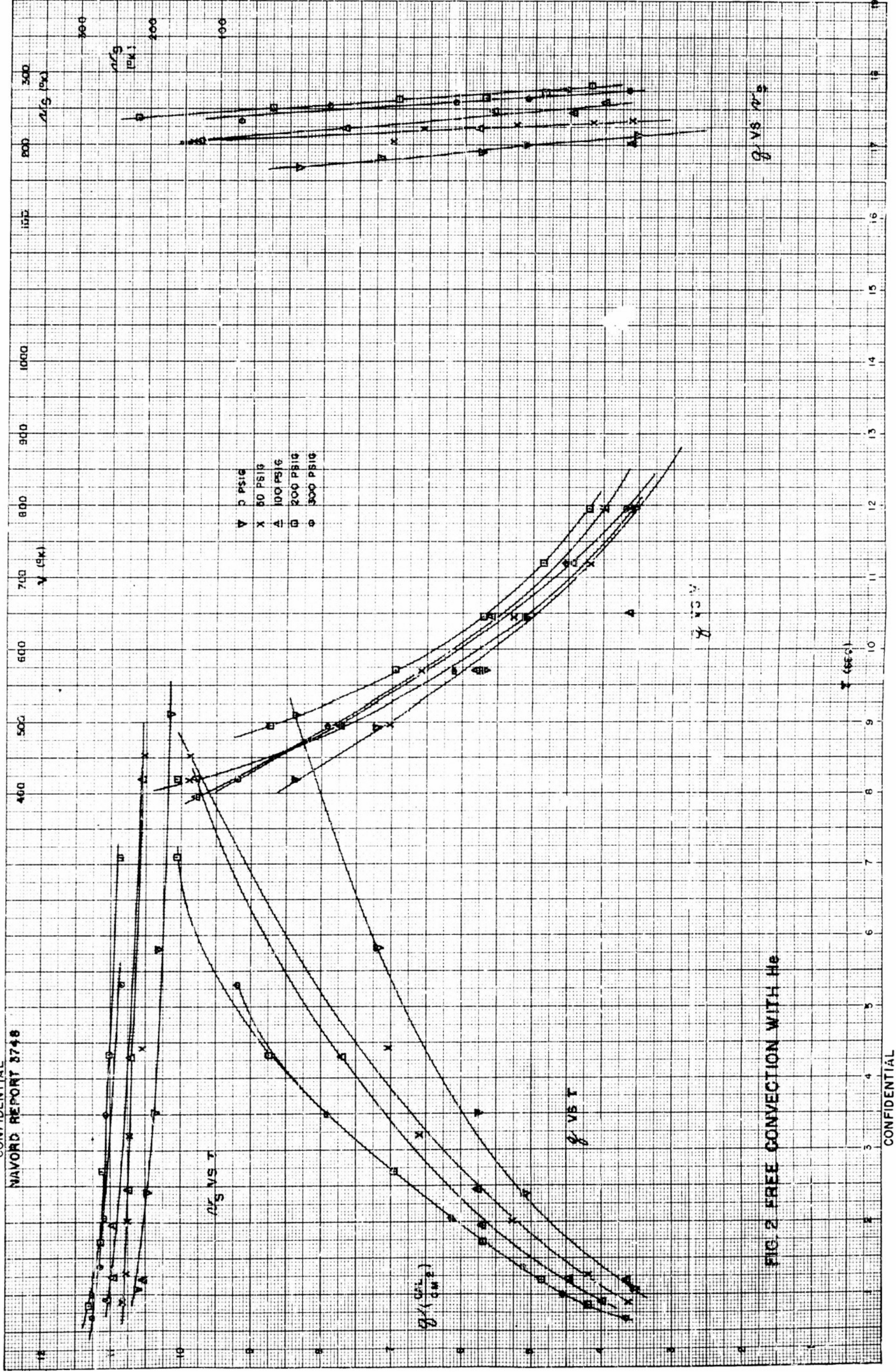
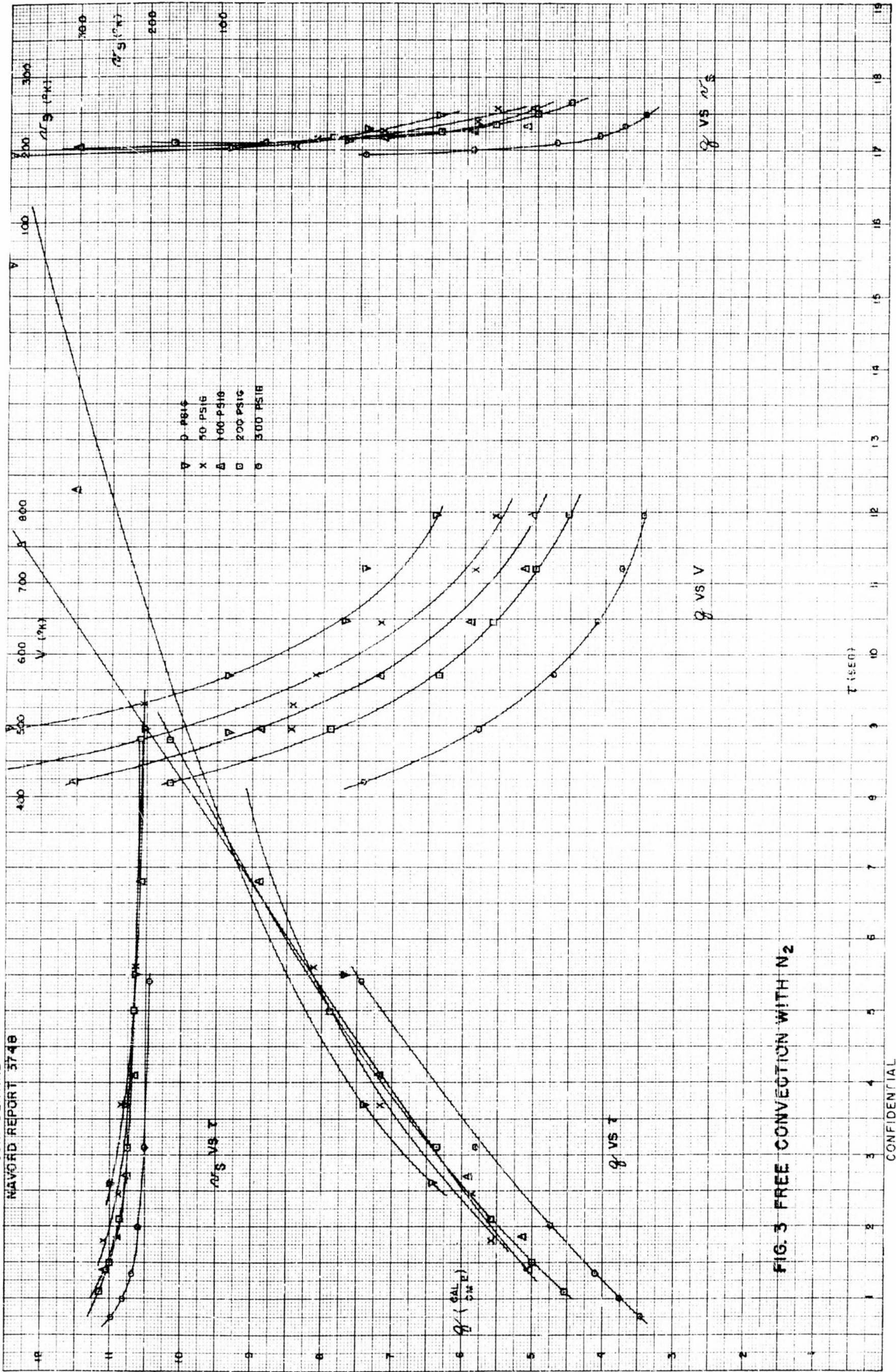


FIG. 2 FREE CONVECTION WITH He

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FIG. 3 FREE CONVECTION WITH N_2

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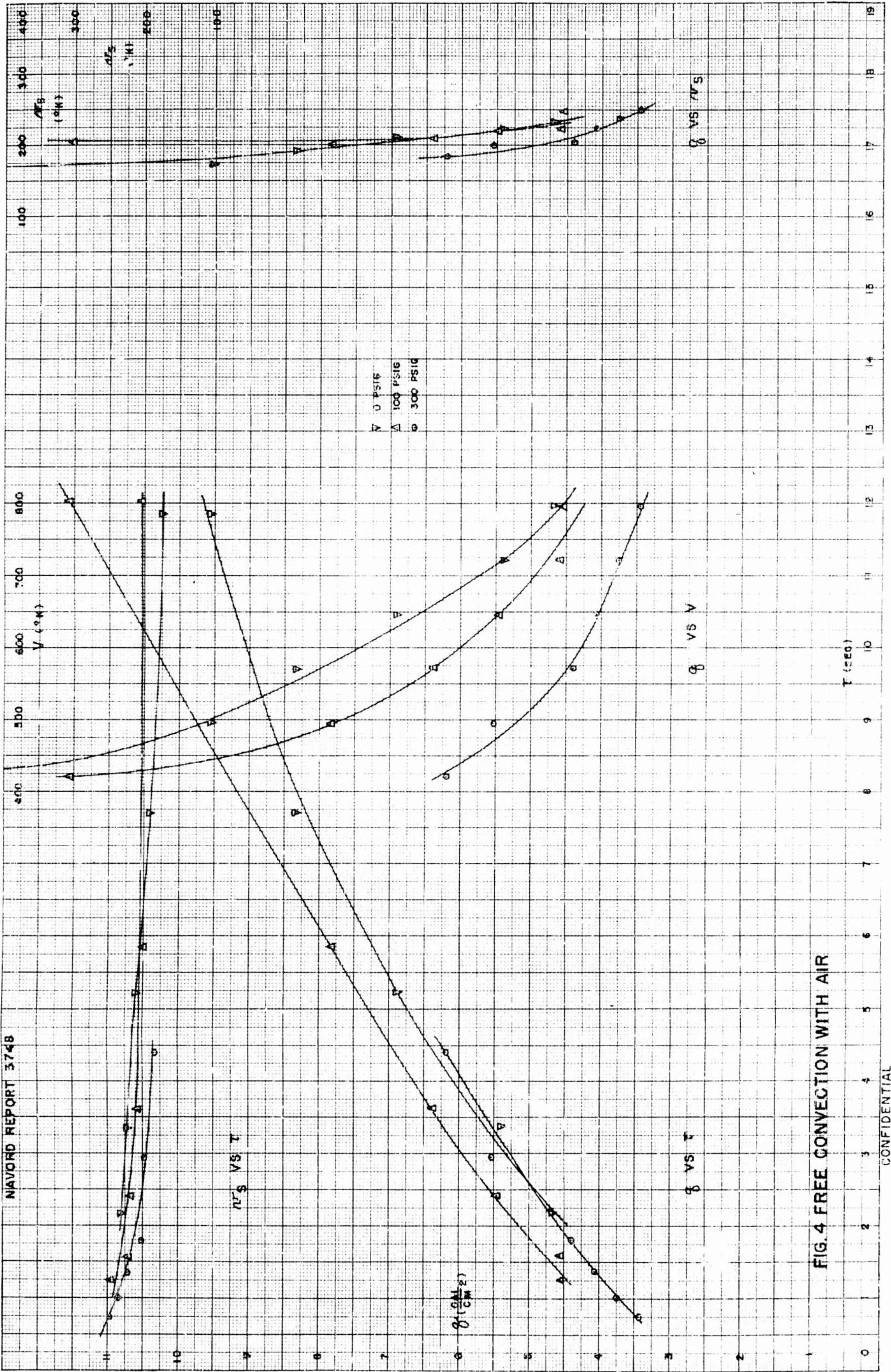


FIG. 4 FREE CONVECTION WITH AIR

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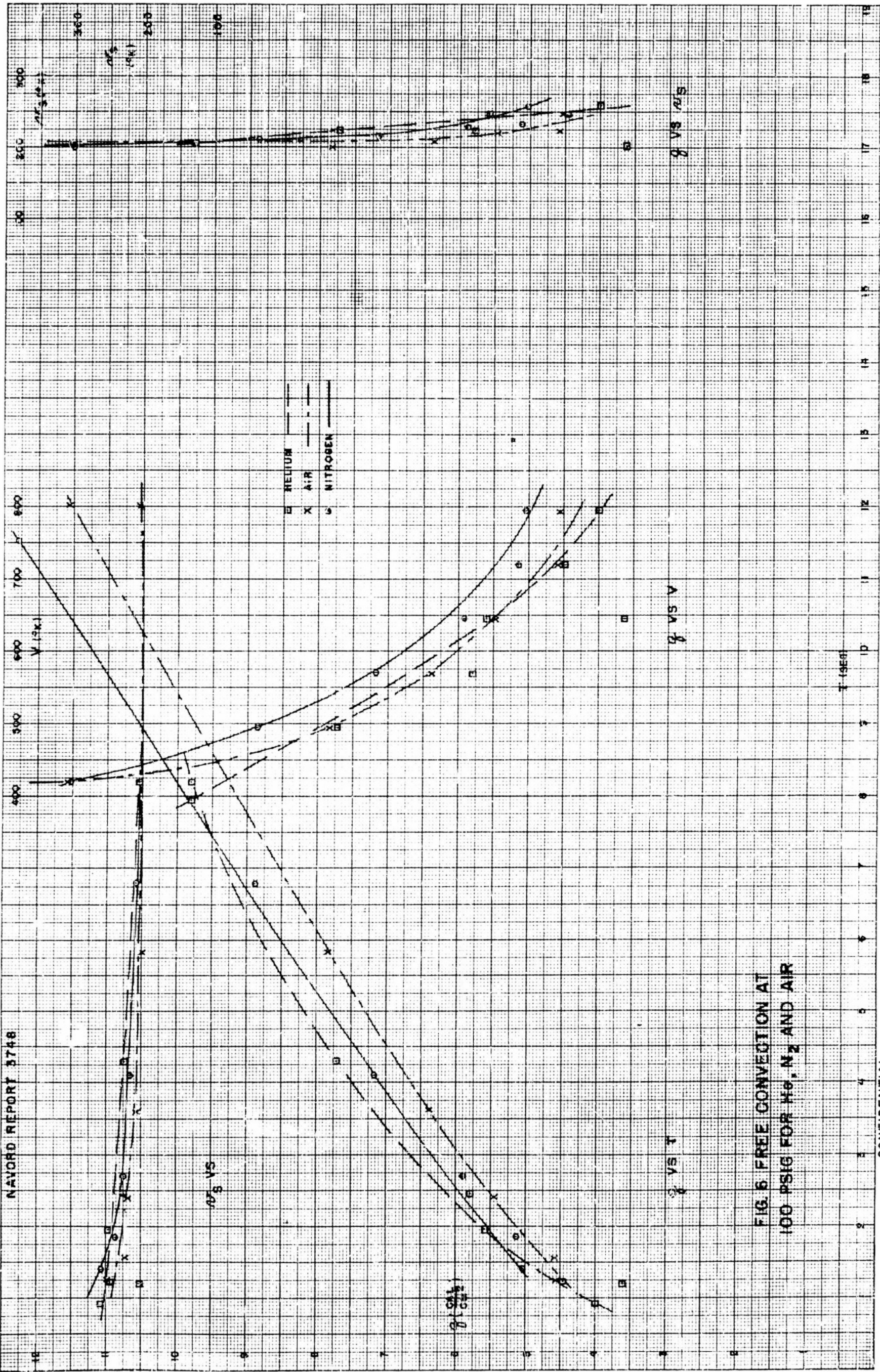


FIG. 6 FREE CONVECTION AT 100 PSIG FOR He, N₂ AND AIR

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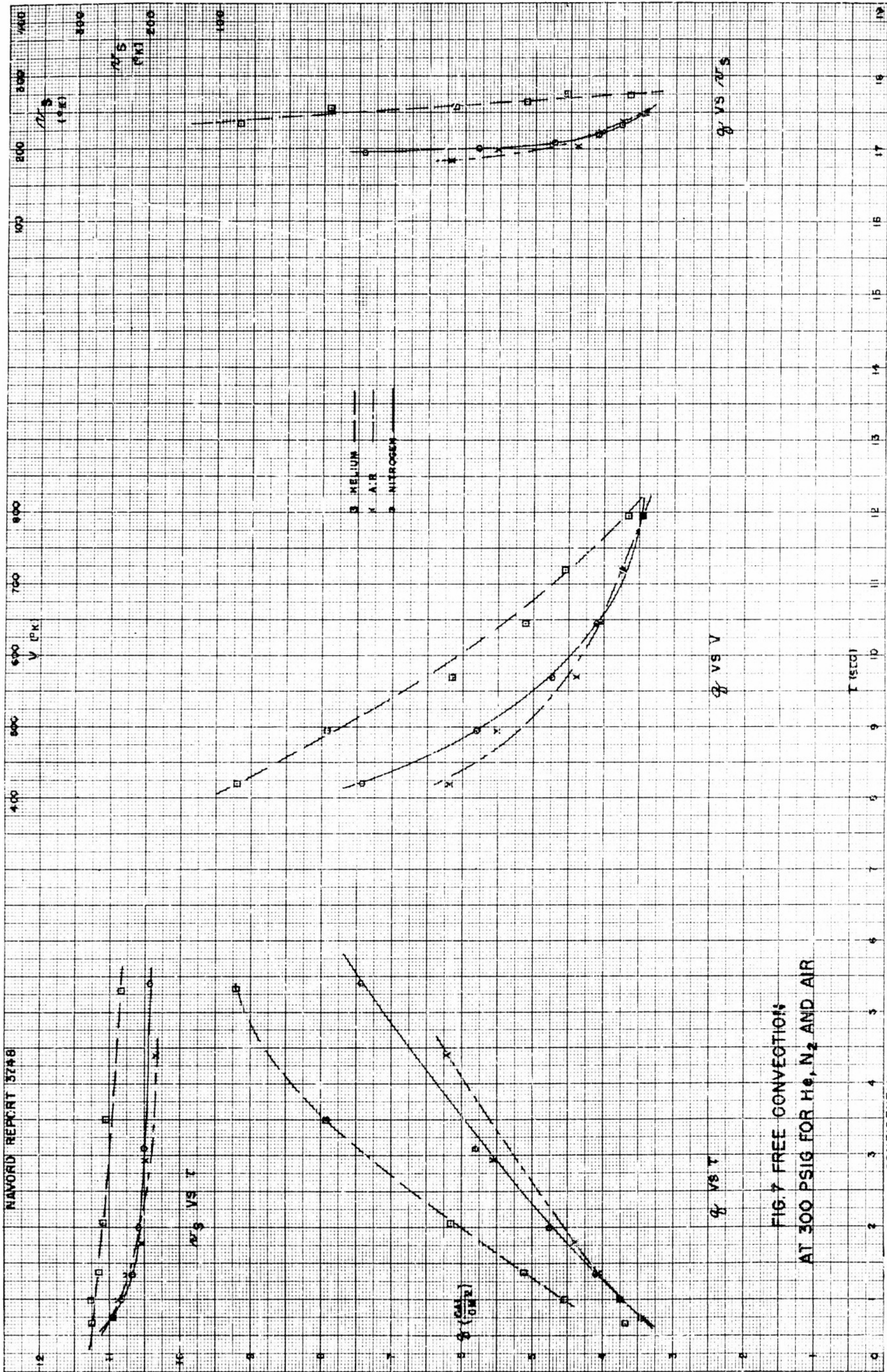


FIG. 7 FREE CONVECTION;
AT 300 PSIG FOR He, N₂ AND AIR

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